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Published in:
Magazine of Concrete Research

DOI:
[10.1680/mac.15.00097](https://doi.org/10.1680/mac.15.00097)

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

[Link to publication in Discovery Research Portal](#)

Citation for published version (APA):
Jones, M. R., Ozlutas, K., & Zheng, L. (2016). Stability and instability of foamed concrete. *Magazine of Concrete Research*, 68(11), 542-549. <https://doi.org/10.1680/mac.15.00097>

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Stability and instability of foamed concrete

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Foamed concrete has proven to be an effective alternative to granular fills and is now widely used internationally. With increasing demand for lightweight materials for buildings in order to improve sustainability, foamed concrete has also developed as an ideal material for this purpose, and many countries utilise construction with precast foamed concrete blocks. However, at densities lower than current technology allows, typically $<500 \text{ kg/m}^3$, foamed concretes are more prone to instability of the fresh mix. Furthermore at very low densities, $\leq 300 \text{ kg/m}^3$, instability is almost inevitable, greatly limiting the potential of foamed concrete for applications where mass is critical (e.g. weak soils, backfilling damaged structure etc.). This paper aims to illustrate the mechanisms of stability and instability in foamed concretes and demonstrates how ultra-low density mixes (down to plastic density of 150 kg/m^3) can be successfully produced.

Notation

| | |
|----------|-----------------------------|
| F_b | bubble buoyancy force |
| F_c | bubble confinement force |
| F_d | drainage force |
| F_{st} | surface tension of bubbles |
| Φ | bubble diameter |
| P_i | internal bubble pressure |
| r | bubble radius |
| γ | interfacial surface tension |

Introduction and background

Foamed concrete is now widely used internationally, but growing pressures for more sustainable construction technologies, such as lightening of structures, energy conservation, minimising the use of primary resources, and resource efficiency, as well as reducing the impact of environmental noise, underpin a need for the development of ultra-low density foamed concrete that current technology is unable to achieve.

‘Conventional’ foamed concrete can be regarded as having a plastic density of $500\text{--}1600 \text{ kg/m}^3$, and ultra-low density foamed concrete has been defined as having a plastic density $\leq 500 \text{ kg/m}^3$. However, it has previously been reported that mixes at these latter densities have greatly increased susceptibility to instability (Aldridge, 2005; Jones and McCarthy, 2005, 2006). Indeed, at $\leq 300 \text{ kg/m}^3$, consistently achieving stable foamed concrete mixes is extremely difficult. Instability of foamed concrete is segregation of the fresh mix due to the separation of solids and air phases in the mix. Generally, this segregation is catastrophic, leading to a complete loss of the air

phase and leaving only the base mix. However, there is no clear understanding of the underlying mechanism of bubble stability in foamed concrete mixes, or why ultra-low density mixes are more prone to becoming unstable.

Working with industry, the authors are aware that this has led to an inability to deploy ultra-low density foamed concrete, even though there is a demand from many construction sectors. Based on laboratory-based studies carried out over a decade, the authors have attempted to develop an empirical understanding of the factors that have been identified as being critical to bubble stability, which are reported here, and thereby develop a method for consistently producing ultra-low density mixes.

Fundamental issues and observations of foamed concrete stability

Effect of plastic density on bubble size

Figure 1 illustrates the typical appearance of instability in foamed concrete mixes, both in a laboratory (Figure 1(a)) and on site (Figures 1(b) and 1(c)). Figure 1(b) illustrates a transition point where a mix is becoming unstable, and bubbles have risen to the surface. This can happen from almost immediately to, more typically, after tens of minutes, but has also been noted up to 24 h after placement. Observationally, the lower the plastic density of the mix, the shorter the time to the onset of instability.

It has been previously noted that foamed concrete average bubble size increases with decreasing plastic density (Jones

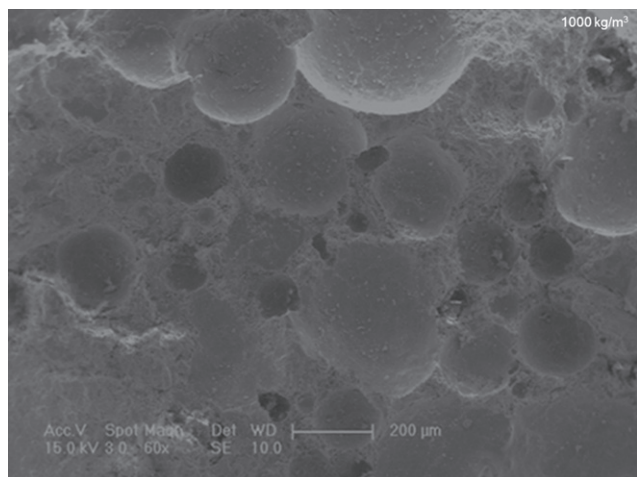


Figure 1. Examples of instability of ultra-low density foamed concrete: (a) in the laboratory; (b) and (c) on site

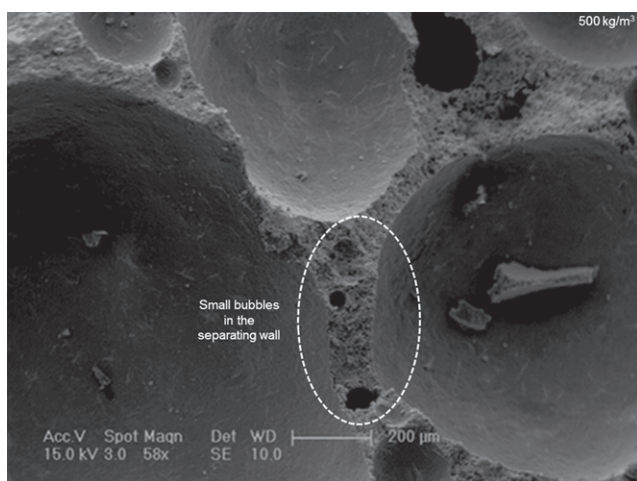
and Zheng, 2013; Nambiar and Ramamurthy, 2007; She *et al.*, 2014; Visagie and Kearsley, 1999). This is, initially, a surprising observation as the nature of the input foam is the same for all mixes and thus bubbles must change size once combined with the base mix. It is not possible to say whether this is an immediate or more gradual process, but it does underline the fact that bubble formation is a dynamic process rather than a simple incorporation of more or less foam into a base mix. It is also not clear whether foamed concrete bubbles

are either larger or smaller than the bubble size of the parent foam, as it is difficult to obtain bubble size metrics in wet foam. However, once this dynamic stage is complete the bubbles form a size essentially proportional to the plastic density of the fresh mix.

Figures 2(a) and 2(b) show typical examples of protein-based foamed concretes with plastic densities of 1000 kg/m^3 and 500 kg/m^3 respectively. This shows that a larger bubble size



(a)



(b)

Figure 2. Comparative bubble size in (a) high and (b) low plastic density foamed concretes

also results in a thinner ‘wall’ separating adjacent bubbles. In addition, these thinner walls tend to contain many more ‘small’ bubbles. It is speculated that these bubbles are due to entrapped air in the base mix, which, when constricted in the thin walls, become more visible. The potential effect of these is discussed below.

Forces acting on bubbles in fresh foamed concrete mixes

Figure 3 is an attempt to provide a two-dimensional (2D) schematic illustration of the ‘forces’ acting on a single bubble when incorporated into fresh foamed concrete. Based on this, a stable equilibrium state of the bubble is obtained when the bubble confinement force (F_c), the drainage force (F_d), internal bubble pressure (P_i), surface tension of the bubbles due to the effect of surfactant (F_{st}) and the bubble buoyancy force (F_b) are balanced.

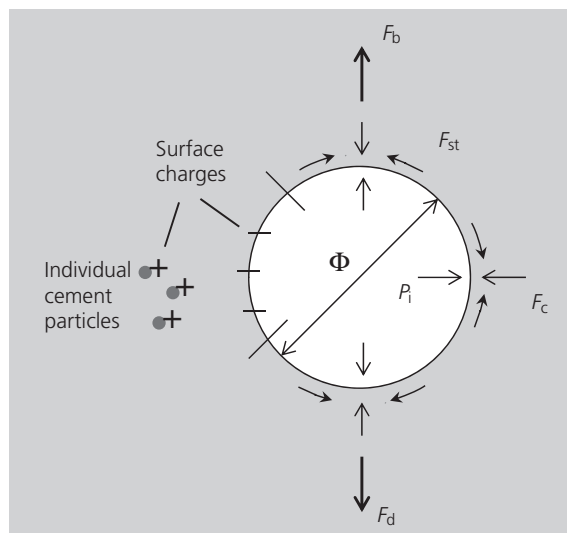


Figure 3. Idealised schematic illustration of forces acting on a single bubble within a fresh foamed concrete mix

The bubble confinement force (F_c) is mainly due to the plastic density of the fresh mix, but the type of constituent materials, such as use of different fillers (e.g. sand or coarse fly ash) and cement type also affect F_c , and can be related to the prevailing mix rheological characteristics of yield stress and plastic viscosity. At densities $\leq 500 \text{ kg/m}^3$, where sand/filler is generally not used, there is likely to be a significant decrease in F_c due to a decrease in yield stress, which results in larger and more closely spaced bubbles. To reach ultra-low densities, both the cement and water contents of the mix have to be reduced and hence F_c is reduced. On the other hand, there is evidence to support the use of finer cementitious materials (such as fly ash) to provide enhanced particle packing around the bubbles and a greater confining force (Nambiar and Ramamurthy, 2007), and hence smaller bubbles given the same overall plastic density.

The initial internal pressure (P_i) of the bubbles is assumed to be the same in the foam prior to incorporation into the base mix, given a particular surfactant type and foam generator pressure. Once the foam is mixed with the cementitious matrix, bubbles change size and the internal pressure varies in order to maintain equilibrium with the surrounding matrix. It is assumed that this process is elastic (Prins, 2006) and hence small bubbles have a higher internal pressure than larger bubbles.

This gives a coherent explanation for the observed bubble size characteristics for different densities, water/cement (w/c) ratios, cement and filler types. Figure 4 provides a schematic illustration of the end result of these force equilibration processes. However, this explanation does not predict instability, and thus additional time-dependent changes to these forces must occur in fresh mixes.

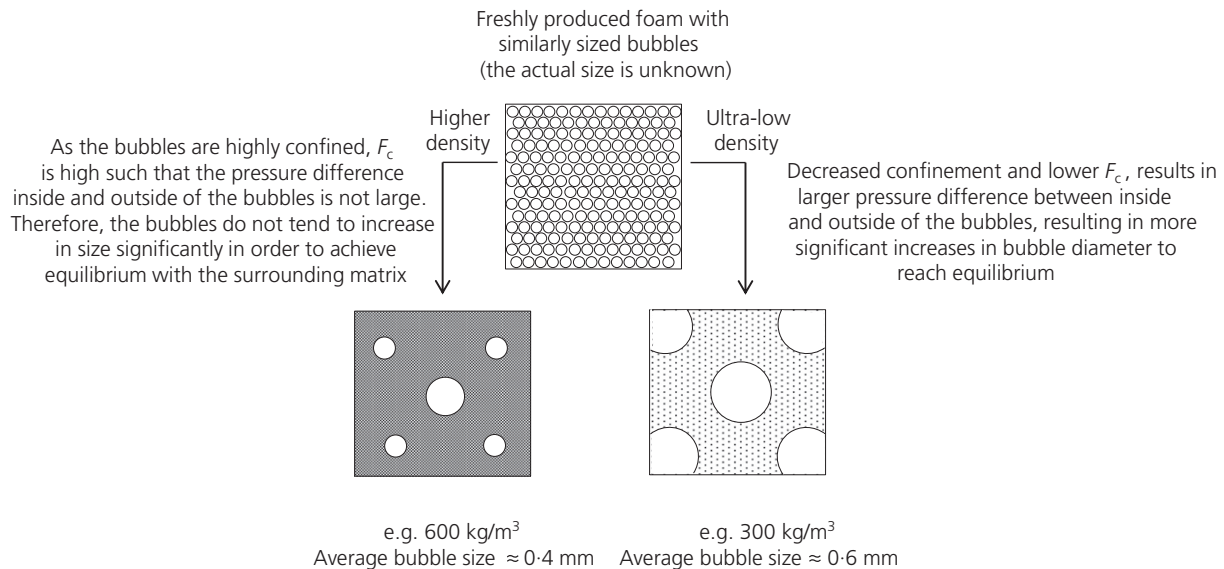


Figure 4. Change in bubble size upon mixing foam with base mix

Causes of stability and instability in mixes of conventional and ultra-low densities

What is clear from observations of unstable mixes is that, at some point in time, the bubble size becomes sufficiently large to cause them to be buoyant and separate from the mix. The following discussion attempts to describe the time-dependent mechanics of buoyant unstable bubbles, and the comparative rate at which this occurs in 'conventional' and ultra-low density foamed concrete mixes.

A major time-dependent force is due to the effect of the surfactant; that is, its control of the surface tension of an aqueous bubble (F_{st}) (Myers, 1992; Weaire and Hutzler, 1999). For liquid foams, the time-dependent effect of surface tension reducing and leading to liquid drainage due to the effects of gravity (F_d) is well understood. As a result, the aqueous/surfactant liquid fraction of the foam changes, and so does the surface tension of the bubbles. In turn, to maintain equilibrium, the bubble size increases (Myers, 1992; Stevenson, 2012; Weaire and Hutzler, 1999). However, unlike liquid foams, bubbles in a cementitious matrix are separated by the paste or mortar phase surrounding them. In this case, the drainage that occurs through thin films separating the bubbles and plateau borders (i.e. channels formed where three neighbouring films meet (Stevenson, 2012)) in liquid foams may change. As a result, it is not possible to directly compare the situation to liquid foams. Stevenson (2012) reported a slower drainage rate in foams with smaller bubbles, suggesting that drainage occurs at a faster rate in lower density foamed concretes than those with high densities. Furthermore, surface charges on the bubbles and cement particles have been reported to affect the mix stability (Jones and McCarthy, 2006). Cement particles are

attracted to bubbles, making it more difficult for the liquid to drain.

As already mentioned, when the mix plastic density is decreased down to ultra-low levels, the total solids content is decreased through reduction and eventual elimination of the sand/filler (below 600 kg/m³), and then the cement and water contents have to be reduced. Figure 4 represents an idealised system in which the bubbles are considered to be of uniform size. However, in reality, there are inevitably a range of actual bubble sizes in a mix, each of which has a slightly different internal pressure.

Varying bubble sizes within a mix give rise to an internal pressure gradient. In turn, this can result in gas diffusion, which is referred to as Ostwald ripening in liquid foams. For aqueous foams, this is driven by the Laplace pressure (Stevenson, 2012; Weaire and Hutzler, 1999), which is $2\gamma/r$ for spheres, γ being the interfacial surface tension and r the bubble radius. In this paper, γ is the surface tension. Due to this differential pressure, the gas contained in smaller bubbles diffuses into larger bubbles, which further increase in size and further increase the pressure differential. The process continues until the bubbles are sufficiently buoyant to float to the surface and burst, releasing the gas contained to the environment. Ultimately, all foamed concretes are destroyed by this process. In mixes where the bubbles are closer together and inter-bubble walls are thinner (i.e. lower density mixes), this process is easier and the process happens more quickly, as shown in Figure 5. The SEM micrographs of low-density foamed concrete mixes shown in Figure 2 show the increased presence of 'small' bubbles within the inter-bubble separating walls.

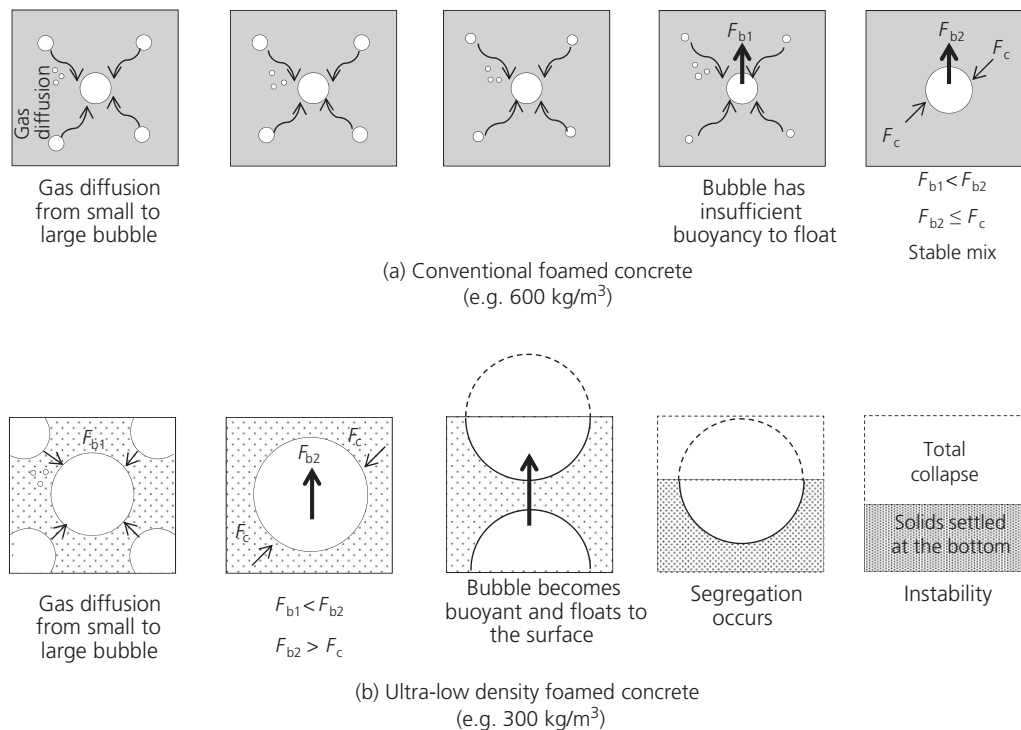


Figure 5. Schematic illustration of inter-bubble gas diffusion and onset of instability in (a) 'conventional' and (b) ultra-low density foamed concrete mixes based on observations

It is speculated that these could further aid inter-bubble gas transfer and hence reduce the time for bubbles to become buoyant.

As a result of an increase in bubble diameter (Φ), the bubble buoyancy force (F_b) increases. Once F_b is high enough to overcome the surrounding F_c , bubbles rise towards the surface of the mix, displacing the surrounding solids and eventually reaching the surface (Figure 1(b)) and causing instability (Figure 1(c)). This dynamic environment exists until equilibrium is reached or the mix hardens. When the mix hardens, no further changes to the bubbles can occur. However, once the non-equilibrium state ($F_b > F_c$) is reached, the process of phase separation is irreversible.

Production of stable ultra-low density foamed concrete

The foregoing discussion, if correct, indicates that the only way to prevent instability is for the mix to 'solidify' prior to bubbles becoming large enough to become buoyant. For denser foamed concretes this is easily achieved within the typical initial set times of Portland cement (PC). However, for ultra-low density foamed concrete this is not fast enough. The authors experimented in the laboratory with a range of high early strength PCs, increased mix temperatures and accelerating admixtures, but none were found to be

consistently successful. Thus, further laboratory trials were undertaken using a blend of PC with a compatible calcium sulfoaluminate (CSA) cement, the results of which are now described.

Constituent materials, mix proportions and production of foamed concrete

The following constituent materials were used to produce foamed concrete mixes for testing.

- CEM I 52.5N (PC) conforming to BS EN 197-1 (BSI, 2011).
- Commercial CSA cement compatible with PC as an additive to provide rapid setting.
- Fine aggregate (natural siliceous sand) conforming to BS EN 12620 (BSI, 2008) category G_F85.
- Surfactant (a commercially available protein-based foaming agent), used in a 6% aqueous solution and foamed to a density of $50 \pm 5 \text{ kg/m}^3$.

The methods used for designing, producing and curing the foamed concrete were as described by Jones and McCarthy (2005), except that a tolerance of $\pm 25 \text{ kg/m}^3$ of the target plastic density was used rather than the more typical $\pm 50 \text{ kg/m}^3$, as the latter could represent 25–50% of the target plastic density.

Test methodologies

Setting time

The initial setting time of the paste fraction was measured with an automatic Vicat apparatus in accordance with BS EN 196-3 (BSI, 2005) using a w/c ratio of 0.5.

Stability

Stability was measured by pouring fresh foamed concrete mixes into 500 mm deep and 75 mm diameter polycarbonate cylinders (see Figure 1(a)) lined with polythene film. The mix was further observed over 24 h for any reduction in height, to measure any longer term instability.

Bubble size analysis

Bubble size analysis was carried out using optical microscopy and automated image analysis software. Test samples were obtained from 500 mm high cylindrical specimens after 28 d of sealed curing. The cylinders were split longitudinally and then sections from the top, middle and bottom (in the direction of cast) of the cylinder were taken and the average of these used to give mean bubble diameters. Broken surfaces were cleaned

of dust and sprayed with fluorescent paint to improve image contrast under UV illumination. A microscope-mounted digital camera was used to capture a 100 mm² image (with resolution of $\approx 2000 \times 2000$ pixels), and 2D image analysis was carried out using ImageJ software (Ferreira and Rasband, 2012), using a similar approach to that described elsewhere (Nambiar and Ramamurthy, 2007; Visagie and Kearsley, 1999).

Results and discussion

Stability

For mixes with plastic densities from 1000 kg/m³ down to 400 kg/m³, 100% PC consistently produced stable foamed concretes. Then, on a trial-and-error basis, lower density mixes were made stable by incorporating CSA cement to partially replace PC. Firstly, 5% of PC (by mass of cement) was replaced with CSA, producing stable 300 kg/m³ and 200 kg/m³ foamed concrete mixes. The CSA content was increased to 10% (by mass of PC) to produce stable 150 kg/m³ density mixes consistently, as summarised in Table 1. Table 2 shows the relationship between collapse and base mix setting times.

| Plastic density: kg/m ³ | Cement: kg/m ³ | | CSA: % by mass of cement | Water: kg/m ³ | Sand: kg/m ³ | Air volume: % |
|---------------------------------------|---------------------------|-----|-----------------------------|-----------------------------|----------------------------|------------------|
| | CEM I | CSA | | | | |
| 1000 | 300 | — | — | 150 | 550 | 55 |
| 600 | 300 | — | — | 150 | 150 | 70 |
| 500 | 335 ^a | — | — | 165 | — | 73 |
| 400 | 267 | — | — | 133 | — | 78 |
| 300 | 190 | 10 | 5 | 100 | — | 84 |
| 200 | 126 | 7 | 5 | 66 | — | 89 |
| 150 | 90 | 10 | 10 | 50 | — | 92 |

^aCement content increased to increase 'fines' content as sand was not used below 600 kg/m³

Table 1. Test mix constituent proportions; a w/c ratio of 0.5 was used for all mixes

| CEM I: % by mass | CSA: % by mass | Base mix initial setting time: hh:mm | Foamed concrete collapse time in the absence of CSA: hh:mm | | | | Stability: Stable (S) or unstable (U) | | | |
|---------------------|-------------------|--|---|------------------|-------|------|---------------------------------------|------|-------|--|
| | | | D150 ^a | D200 | D300 | D150 | D200 | D300 | >D300 | |
| 100 | — | 03:25 | 01:10 | 01:40 | 01:55 | U | U | U | S/U | |
| 95 | 5 | 01:30 | n/m ^b | n/a ^c | n/a | U | S/U | S | S | |
| 90 | 10 | 00:20 | n/a | n/a | n/a | S | S | S | S | |

^aD is plastic density value in kg/m³

^bNot measured

^cNot applicable

Table 2. Collapse and initial setting times; w/c ratio=0.5

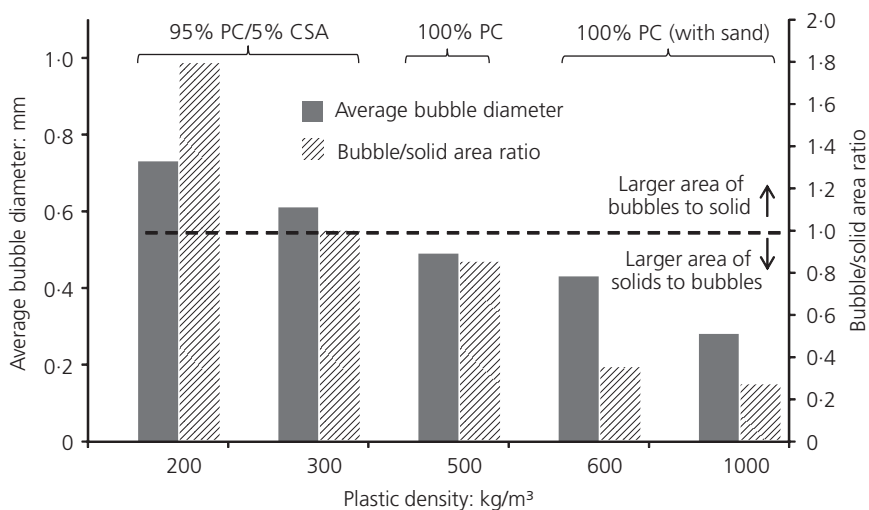


Figure 6. Bubble size characteristics of stable foamed concrete mixes

It was not possible to produce mixes with plastic densities below 150 kg/m^3 as the CSA content had to be increased above 10%. This caused the base mix to set within 2 min and there was insufficient time to incorporate foam and place the foamed concrete. However, with the use of CSA set controllers, producing stable foamed concrete below 150 kg/m^3 could be possible.

Bubble size analysis

Figure 6 summarises the results of bubble size analysis carried out by 2D image analysis in relation to stability. As expected, bubbles increased in diameter in the ultra-low density foamed concretes. The average bubble diameter increased 2.6 times from the highest to lowest density. The 150 kg/m^3 density samples did not split cleanly but fractured into multiple pieces, and thus it was not possible to carry out analysis on these samples.

Figure 6 also gives the calculated bubble to solid area ratio obtained from the 2D image analysis. As the plastic density decreased this ratio increased due to the increased air content at 300 kg/m^3 density, where stability issues commence with utilisation of 100% PC, the bubble to solid area is around 1. As discussed earlier, the buoyancy force of the bubble (F_b) will then tend to be similar to the 'confinement' force (F_c) and such mixes will be on the borderline between being stable or becoming unstable with typical PC set times.

Conclusions

By considering the internal forces likely to be affecting bubbles and the surrounding paste/mortar fractions of foamed concrete, it is possible to present a coherent reasoning and mechanism to explain instability in fresh foamed concrete mixes.

The underlying cause of instability is considered to be the buoyancy force of the bubbles, which allows them to float out of a fresh mix and ultimately cause complete separation of the gas and solid phases. The buoyancy force is directly related to bubble size, and this becomes significantly larger at lower densities; larger bubbles are consequently much more buoyant and hence lower density mixes are more prone to instability.

This is explained by the observation that, as the air content fraction is increased in lower density mixes, the 'confinement' force due to the solids is reduced. In addition, larger bubbles and a smaller solids fraction result in bubbles being closer and the separating walls thinner. Established theory predicts that this makes it easier for gas to diffuse from smaller (high internal pressure) to larger (low internal pressure) bubbles, and hence the bubbles become more buoyant over time. At a critical time, related to the bubble buoyancy, separation of solid and gas phases (i.e. instability) occurs and the fresh mix collapses. Following extensive laboratory trials, the best method of overcoming this was found to be the blending of rapid-setting CSA cement with the PC.

The practical issues of placing ultra-low density foamed concretes with base mixes produced from cement with an initial setting time of 20–25 min are problematic. Further research is needed to develop methods to retard the initial setting times for transportation and mixing, and then activate it immediately when rapid hardening is needed after placement.

Acknowledgements

The authors wish to acknowledge Propump Engineering Ltd for help and discussions. Thanks also go to CALTRA Nederland BV for their support with the supply of CSA.

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